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LEIR-PS TRAJECTORY MEASUREMENT

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Abstract

The trajectory of the extracted ions from the Low Energy Ion Ring (LEIR) to the PS will have to be measured and stored every 3.6s. The existing LEAR Pick-ups (PUs) are re-used, but the front end electronics and acquisition system have been changed. This note addresses the requirements for the trajectory measurement, as well as the hardware and software, which has been developed and installed.

Geneva, Switzerland
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1. Introduction

The LEIR nominal cycle (Figure 1) has a length of 3.6 s, and accumulates 4 multi turn injections of 4.2 [MeV/u] lead ions (Pb^{54+}) on the flat bottom. Every injected beam is electron cooled and moved to a "stack orbit". After the 4 injections the beam is bunched, accelerated and extracted to the PS at an energy of 72.2 [MeV/u] with a relativistic beta of 0.373. The two (or one) extracted bunches have a length of 100-200 ns (~20 m) and an intensity varying between 10^9-$2*10^{11}$ charges.

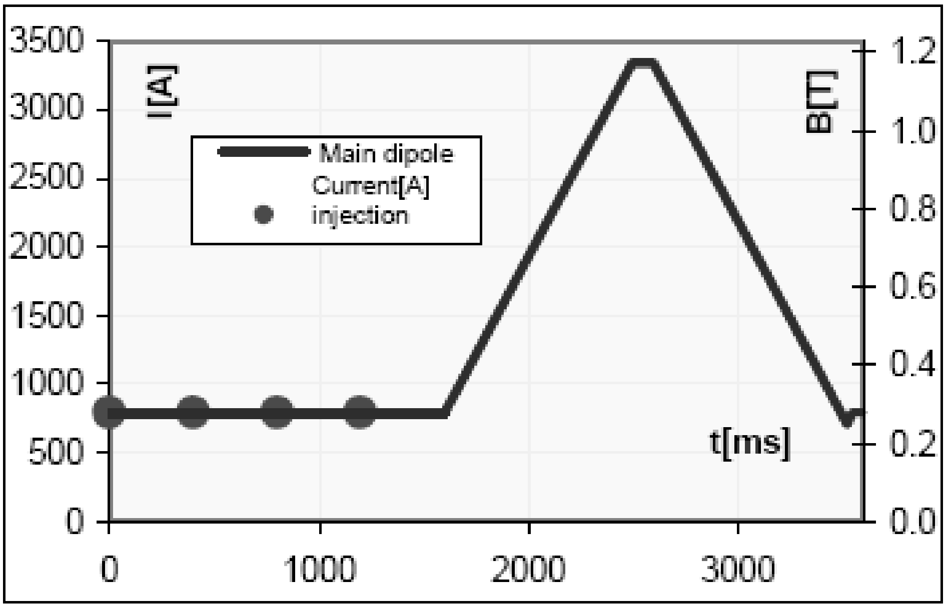

Figure 1: LEIR cycle

In the former LEAR injection line, 7 horizontal and 7 vertical electrostatic PUs were installed in 1986, from which four were moved to the AD in 1999 after LEAR was shut down. To replace those, 4 new PUs identical to the old ones have been constructed and have been installed in the LEIR ETL line.
The cylindrical PUs exist in three different diameters, and are made of stainless steel (316 LN) sheets, accurately cut and bent, mounted in metal tubes which are fitted inside the vacuum chamber. One annular electrode provides the intensity signal (Σ), and the difference signal (Δ) is derived from a v-cut cylinder, forming two semi-sinusoidal electrodes. All of the PUs are bake able up to 300° C. The Δ/Σ-ratio together with the PU sensitivity provides an intensity independent position measurement. The characteristics of the PUs are resumed in Table 1 and a PU is shown in Figure 2.

Vacuum chamber diameter [mm]	140 / 172 / 243
Physical length [mm]	320
Electrical Length Δ / Σ [mm]	71 / 53
Capacitance per electrode [pF]	~100
Differential sensitivity [V/mm]	$48*10^{-15}*N*B_f$
Sigma sensitivity [V]	$845*10^{-15}*N*B_f$

Table 1: PU parameters

Where N is the number of charges and B_f is the bunching factor defined as: $\hat{i}/\bar{i}$.

Figure 2 : LEIR extraction line electrostatic PU

2. Requirements

The requirements for the trajectory measurement and some of the beam parameters are summarised in Table 2.

Max. displacement [mm]	±70
Position resolution @ 10^9 Ch. [mm]	1
Position resolution @ 10^{10} Ch. [mm]	0.1
Absolute precision in centre [mm]	0.3
Relative precision [%]	1
Bunch lengths [ns]	100 - 200
Bunch lengths [m]	~20
Revolution period @ ejection, Pb(54) [ns]	700
Intensity / bunch [Ch.]	10^9 - $2*10^{11}$
Vacuum [Torr]	10^{-9} - $3*10^{-12}$
Bake out temperature [ºC]	300

Table 2: Requirements and beam parameters

3. PU signals and analogue electronics

3.1. Expected PU signals

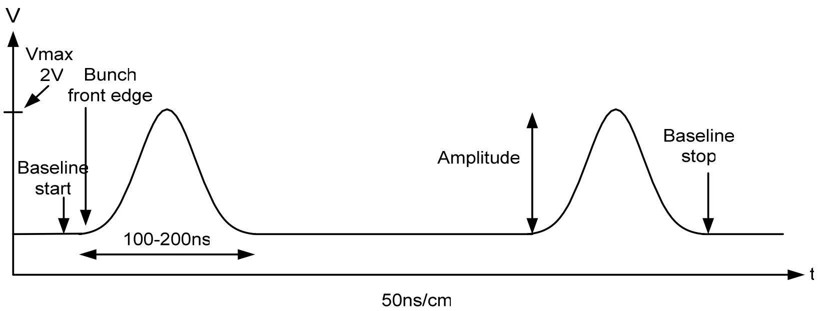

Figure 3: Expected signals in control room

Figure 3 shows an expected sigma signal, the delta signal is much smaller in amplitude but identical in time.

3.2. Analogue electronics

The layout of the acquisition system is shown in Figure 4 and consists of a head amplifier mounted close to the PU, followed by differential transmission of the Δ and Σ-signals to a rack (RA H061) close to the control room. Then a reception amplifier transforms the signals to single ended and splits them to several users, such as local observation, OASIS and the digital acquisition system, which will be described later. The cables and the reception amplifiers from LEAR are re-used as well as an existing calibration generator, which generates 200 ns pulses of 1.8V amplitude.

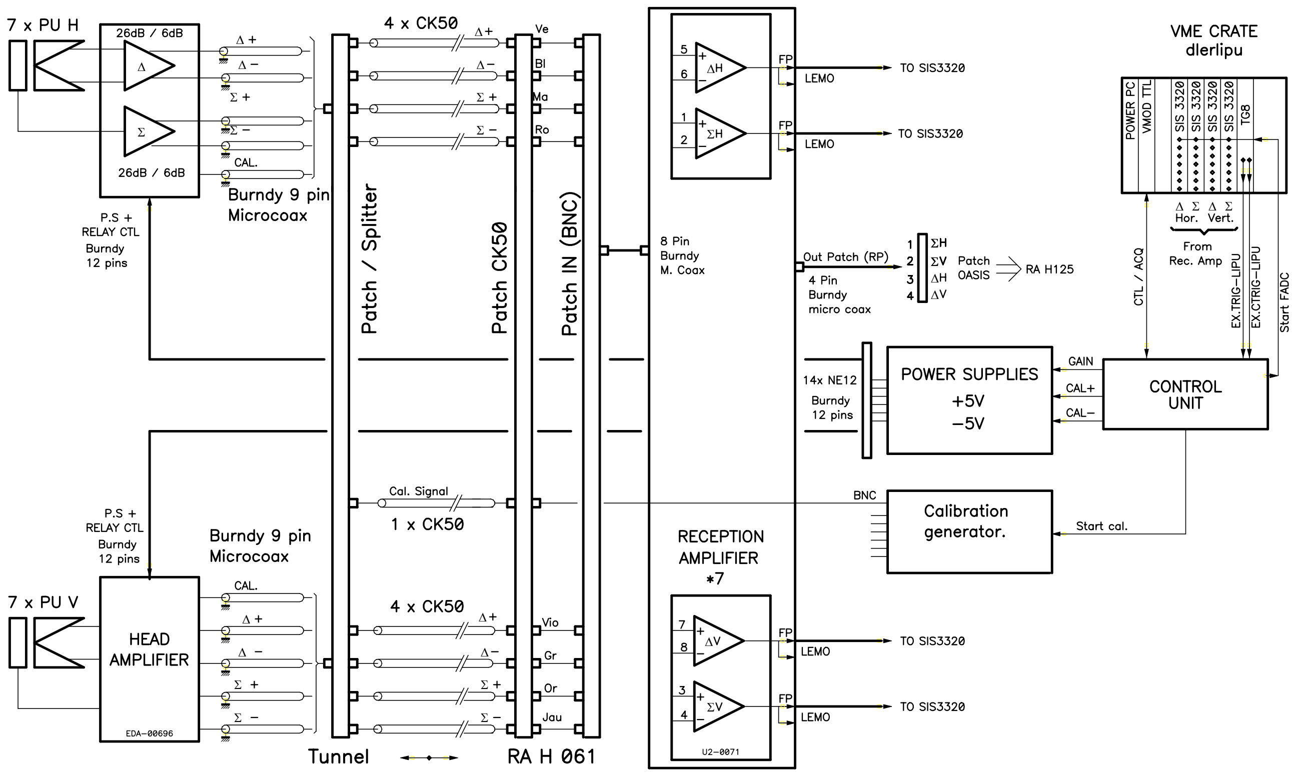

Figure 4: LEIR ejection line trajectory measurement system

3.2.1. Head amplifier

In order to comply with the resolution requirement of 1 mm at 10^9 charges and the intensity range of ~100, the head amplifier has 2 different gains. The high gain of 20 times is determined such as to have at least 3mV (3 LSB) delta signal at 1 mm and 10^9 charges per bunch and will saturate at $3*10^{10}$ charges. For higher intensities (lighter ions) the low gain should be used. The low frequency cut off insures a droop of the signals less than 0.5%, and the high frequency cut off is determined by the necessity of observing bunches < 100 ns long.

	Low Gain	**High Gain**
Gain [dB]	6	26
Bandwidth [MHz]	0.003-100	0.003-100
CMRR @10MHz [dB]	60	60
Max. Output voltage [V]	2	2
Input / Output impedance [Ω]	220k / 50	220k / 50
Equivalent input noise [$nV/\sqrt{Hz}$]	12	5

Table 3: Head amplifier specifications

3.2.2. Reception amplifier

The old LEAR reception amplifiers are re-used for the first run, but will be replaced with a newly developed similar module during 2006. The purpose of this module is to “receive” the differential PU signals and to distribute them single ended to several users. The performance of the reception amplifiers is resumed in Table 4.

Gain (single ended) [dB]	-6
Bandwidth [MHz]	0.0003-110
CMRR @1MHz [dB]	60
Max. In / Out-put voltage [V]	2
Input / Output impedance [□]	50
Nb. of channels, 1□3	4

Table 4: Reception amplifier specifications

4. Fast digitisation

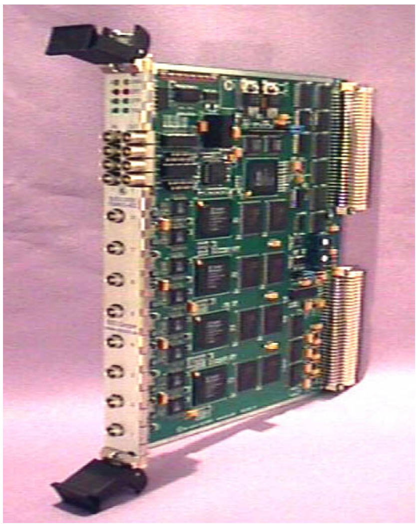

Figure 5: SIS3320

The Δ and Σ-signals are digitized at a fast rate (200MS/s) and digital detection, integration, baseline correction and normalisation, are done by software. The module chosen is an eight channel VME based, fast ADC from SIS (Struck Innovative Systems), the SIS3320. The specification of the module is given in Table 5.

Number of channels	8
Resolution [Bits]	12
ENOB [Bits]	11
Max. sampling rate [MS/s]	210
Input range [V]	±2
Analogue bandwidth [MHz]	> 100MHz
Input impedance [Ω]	50
Clock	Ext. / Int.
Memory per channel	32 MSamples

Table 5: SIS3320 specifications

PU name	SIS3320 Mod / Ch	PU name	SIS3320 Mod / Ch
EE.UEH1O	ΔH = 1 / 1	ETL.UEV30	ΔV = 2 / 7
	ΣH = 1 / 2		ΣV = 2 / 8
EE.UEV1O	ΔV = 1 / 3	ETL.UEH20	ΔH = 3 / 1
	ΣV = 1 / 4		ΣH = 3 / 2
EE.UEH20	ΔH = 1 / 5	ETL.UEV20	ΔV = 3 / 3
	ΣH = 1 / 6		ΣV = 3 / 4
EE.UEV20	ΔV = 1 / 7	ETL.UEH10	ΔH = 3 / 5
	ΣV = 1 / 8		ΣH = 3 / 6
ETL.UEH40	ΔH = 2 / 1	ETL.UEV10	ΔV = 3 / 7
	ΣH = 2 / 3		ΣV = 3 / 8
ETL.UEV40	ΔV = 2 / 3	EP.UEH10	ΔH = 4 / 1
	ΣV = 2 / 4		ΣH = 4 / 2
ETL.UEH30	ΔH = 2 / 5	EP.UEV10	ΔV = 4 / 3
	ΣH = 2 / 6		ΣV = 4 / 4

Table 6: FADC channel allocation

5. Timings

The following fast timings needed to trigger the FADCs in beam and calibration modes, have been installed in the DSC:

EX.TRIG-LIPU:
This timing is used to acquire the extracted beam and is synchronized with the extraction kicker timing which is connected to the external input on channel 1 on the CTR-V module. Channel 5 on the CTR-V module .

EX.CTRIG-LIPU:
This is a burst of 6 pulses separated by 80 ms when the calibration is activated, and which is used to acquire the calibration pulses. Six pulses are needed to make a complete calibration, in order to simulate maximum, centered and minimum beam position in both gains. Channel 2 on the CTR-V module.

Depending on the mode, one of the two triggers is chosen in the control module and used to trigger the SIS3320 FADCs.
In order to acquire the data stored in the FADCs 2 slow interrupts have been foreseen:

EX.PUB-LIPU:
Comes out once at the end of each cycle. Used to wake up the front-end “beam” software after the trajectory has been digitized (previewed time for digitizing is 5.12 us). It is derived from EX.STRIG-RIPU with delay 6 us. Ch 6 on the CTR-V module.

EX.CAL-LIPU:
Used after every calibration pulse with 6 us delay to wake up the front end “calibration” software, in order to compute the coefficients derived from the calibration pulses. Ch 7 on the CTR-V module.

6. Controls

To control the head amplifier gain and calibration relays, one VMOD TTL module is foreseen, and has the following bit allocation:

Signal	Pin	Direction	Function
Port A D0	1	OUTPUT	Low gain CTL, Low gain = “1”
Port A D1	25	OUTPUT	Spare
Port A D2	2	OUTPUT	Cal + CTL, On = “1”
Port A D3	24	OUTPUT	Spare
Port A D4	3	OUTPUT	Cal – CTL, On = “1”
Port A D5	23	OUTPUT	Spare
Port A D6	4	OUTPUT	Spare
Port A D7	22	OUTPUT	Spare
Port B D0	6	INPUT	Low gain ACQ, Low gain = “1”
Port B D1	20	INPUT	Spare
Port B D2	7	INPUT	Cal + ACQ, On = “1”
Port B D3	19	INPUT	Spare
Port B D4	8	INPUT	Cal – ACQ, On = “1”
Port B D5	18	INPUT	Spare
Port B D6	9	INPUT	Loc / Rem ACQ, “0” = Rem.
Port B D7	17	INPUT	Spare
Port C D0	11	Not defined	Spare
Port C D1	15	Not defined	Spare
Port C D2	12	Not defined	Spare
Port C D3	14	Not defined	Spare

Table 7: Control and acquisition bit allocation

Please note that a centred beam is simulated with Cal+ and Cal- switched on simultaneously.
The interface between the VMOD TTL and the amplifiers is via a control module installed in a NIM crate.

7. Software

The front-end software reads 14 Δ and Σ-signals and stores them in arrays. The software detects the bunches from the raw data, and calculates the integration gate (Figure 3) as well as the baseline.
The sigma signal is used to detect the front edge of the bunches, and since the delta signals are digitized using the same clock, they are read at an identical relative memory location. Please note that the amplitude for the delta signal on the reference trajectory is zero, and that the sigma signal must be higher than a certain threshold level, below which the data are rejected. The baseline levels are measured at the beginning and at the end of digitization period of 5120 ns. In order to obtain more stable baseline detection, averaging of the first 95 ns and last 95 ns of the signal is used. The baseline is calculated as the line passing through the baseline start and stop amplitudes. Once the baseline level has been corrected, the Δ and Σ-signals are integrated, and the obtained values are used to calculate the overall positions for every PU. The baseline corrected and scaled (but not integrated) momentary positions are stored and can be displayed with the Sampler system or an equivalent virtual oscilloscope.
Two modes of operation are implemented in the front-end software:
* **Beam:** The 14 beam positions (overall or per bunch) are calculated using scaling factors (k) measured in calibration mode:

$$Pos. = unitFactor \cdot \left(k \cdot \frac{\int_{T_i} (\Delta - B_\Delta) dt}{\int_{T_i} (\Sigma - B_\Sigma) dt} + offset \right)$$

where

$offset$ = electrical offset (a0) + mechanical offset,

B_Δ, B_Σ - baselines for the difference signal (Δ) and the intensity signal (Σ),

k – scaling factors measured in the calibration mode,

T_i – area of the bunch (up to 2 bunches), sigma > sigmaThreshold).

The real beam signals in the first PU (registered on 24.04.2006) are shown in Figure 6 below. In other PUs the signals have the same structure but they are shifted in time.

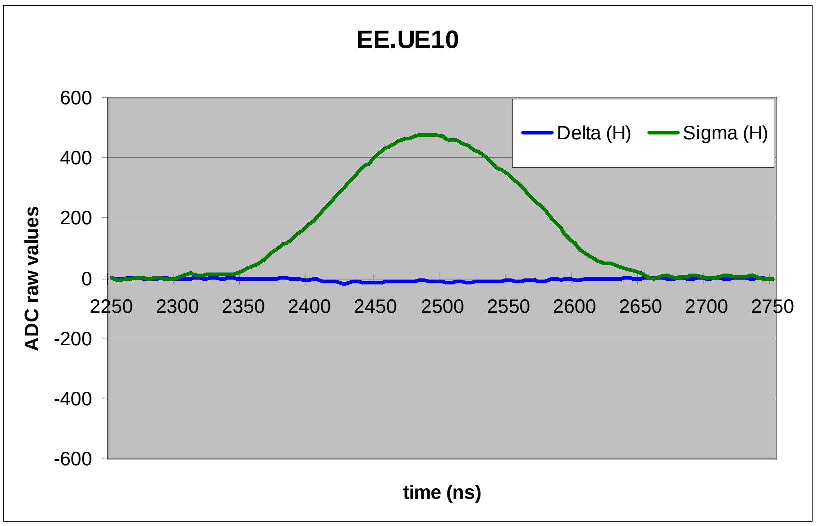

Figure 6: Real beam signals in control room

* **Calibration:** The pick-ups represent systematic errors that must be corrected for. These come from mechanical and electrical offsets and from gain differences in the amplification chain. The mechanical offsets have been measured after installation and the electrical ones during bench testing. Both values are rarely changing and are provided as constant tables. The sensitivity of the PUs varies from PU to PU and again these values are provided as persistent values.
Gain differences can be measured during a calibration procedure during which calibration data are stored in calibration tables.
The calibration is done on request and one single 200 ns pulse is used to simulate the beam. With the help of relays on the head amplifier input, the calibration signal is connected to the input of the amplifier, in order to simulate the beam and measure the ratio of the Δ and Σ-gains of the electronics.

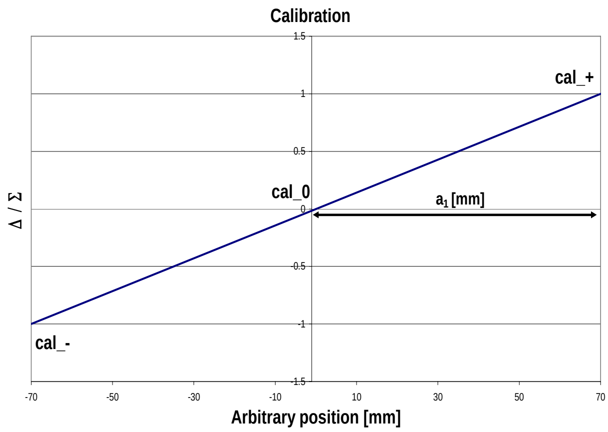

Figure 7: Calibration

- **Cal_+:** Simulates the maximum positive beam displacement.
- **Cal_0:** Simulates a centred beam.
- **Cal_–:** Simulates the maximum negative beam displacement.
- The slope of the line which is determined by the $\frac{\Delta_{Gain}}{\Sigma_{Gain}}$ is used to normalise the beam position measurements such that:

$$k = \frac{2 * a_1}{\frac{\Delta_{Cal+}}{\Sigma_{Cal+}} - \frac{\Delta_{Cal-}}{\Sigma_{Cal-}}}$$

Every PU has been measured on a test bench and their sensitivities $\mathbf{a_1}$ (position where Δ=Σ) and electrical offsets $\mathbf{a_0}$ are known.
Since there is no DC coupling in the analogue part, no offset drift is possible and Cal_0 is thus only used to verify the Common Mode Ratio rejection (CMRR) of the head amplifier.
The calibration Cal– signals in the first PU (registered on 24.04.2006) are shown in Figure 8 below. In other PUs the calibration signals have the same structure but they are shifted in time.

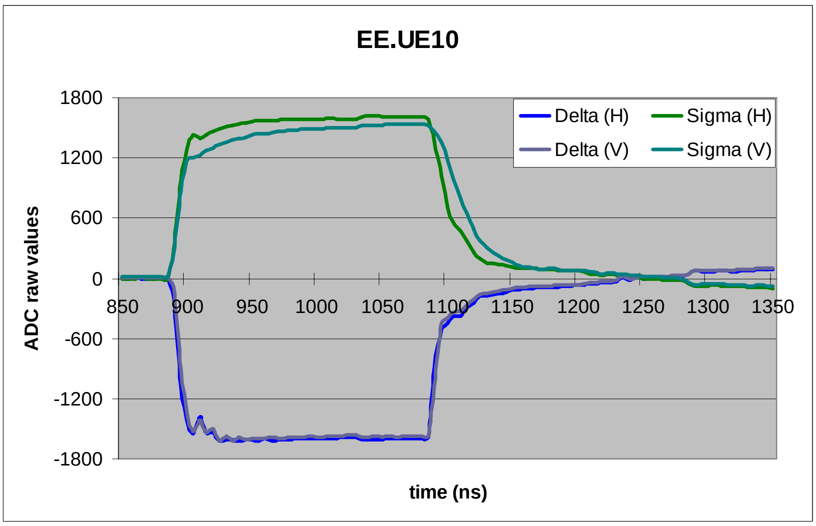

Figure 8: Calibration signals in control room

Additional information about front-end software can be found in the documents "BI Front End Software Functional Specifications for the Beam Trajectory Measurement in the Transfer Lines between the LEIR and the PS [BPMLE]" and "BI Front End Software Interface for the Beam Trajectory Measurement in the Transfer Lines between the LEIR and the PS [BPMLE]" (CERN EDMS Ids 706899 & 706896).

8. OASIS

All the delta and sum signals are connected to the OASIS system and the details can be found in the Table 8 below. The cable numbers refer to the signal cable between RA H061 and RA H125.

Name	Cable number	VME chassis	rang	Patch panel	OASIS cable	OASIS ch.
EE.UEHV10SH-AS	2606775	dleioas2	74	PPA-1	LEI61	1
EE.UEHV10SV-AS	2606776	dleioas2	75	PPA-2	LEI62	2
EE.UEHV10DH-AS	2606777	dleioas2	76	PPA-3	LEI63	15
EE.UEHV10DV-AS	2606778	dleioas2	77	PPA-4	LEI64	16
EE.UEHV20SH-AS	2606779	dleioas2	78	PPA-5	LEI65	17
EE.UEHV20SV-AS	2606780	dleioas2	79	PPA-6	LEI66	18
EE.UEHV20DH-AS	2606781	dleioas2	80	PPA-7	LEI67	31
EE.UEHV20DV-AS	2606782	dleioas2	81	PPA-8	LEI68	32
ETL.UEHV40SH-AS	2606783	dleioas2	82	PPA-9	LEI69	33
ETL.UEHV40SV-AS	2606784	dleioas2	83	PPA-10	LEI70	34
ETL.UEHV40DH-AS	2606785	dleioas2	84	PPA-11	LEI71	47
ETL.UEHV40DV-AS	2606786	dleioas2	85	PPA-12	LEI72	48
ETL.UEHV30SH-AS	2606787	dleioas2	86	PPA-13	LEI73	49
ETL.UEHV30SV-AS	2606788	dleioas2	87	PPA-14	LEI74	50
ETL.UEHV30DH-AS	2607166	dleioas2	88	PPA-15	LEI75	63
ETL.UEHV30DV-AS	2607167	dleioas2	89	PPA-16	LEI76	64
ETL.UEH20SH-AS	2607168	dleioas2	90	PPA-17	LEI77	65
ETL.UEH20SV-AS	2607169	dleioas2	91	PPA-18	LEI78	66
ETL.UEH20DH-AS	2607170	dleioas2	92	PPA-19	LEI79	79
ETL.UEH20DV-AS	2607171	dleioas2	93	PPA-20	LEI80	80
ETL.UEHV10SH-AS	2607172	dleioas2	94	PPA-21	LEI81	81
ETL.UEHV10SV-AS	2607173	dleioas2	95	PPA-22	LEI82	82
ETL.UEHV10DH-AS	2607174	dleioas2	96	PPA-23	LEI83	95
ETL.UEHV10DV-AS	2607175	dleioas2	97	PPA-24	LEI84	96
ETP.UEHV10SH-AS	2607176	dleioas2	98	PPA-25	LEI85	97
ETP.UEHV10SV-AS	2607177	dleioas2	99	PPA-26	LEI86	98
ETP.UEHV10DH-AS	2607178	dleioas2	100	PPA-27	LEI87	111
ETP.UEHV10DV-AS	2607179	dleioas2	101	PPA-28	LEI88	112

Table 8: OASIS signals

9. Results and overall performance

All the PUs have been measured on a test bench and their sensitivities and electrical offsets have been quantified. A plot of such a measurement is shown in Figure 9 below, together with a plot of the error compared to a linear fit. The maximum relative error of ~0.6 mm occurs at -60 mm. For beam positions within ±30 mm the error is within ±0.3 mm (1%).

The position resolution is not limited by the analogue noise levels but by the granularity of the ADC. The LSB of the 12 bit ADC is 1mV and is in the following considered to be equal to the resolution. In order to have a resolution of 1 mm at 10^9 charges the necessary gain of the head amplifier has been evaluated to 20 times. With this gain and a fully offset beam (70 mm) the system would saturate slightly below 10^{10} charges. In a transfer line it is very likely that the beam will be close to the centre of the vacuum pipe and the gains have thus been optimised for resolution rather than maximum possible displacement. In Figure 10 is shown a plot of the expected resolution and the maximum displacement before saturation of the system. Note that due to the different sensitivities of the Δ and Σ-signals, saturation in high gain will occur at 3E10 Ch. for the

Σ–signal, and at 19 mm and 3E10 Ch. for a 140 mm diameter PU. In Table 9 a summary of the overall performance is shown.

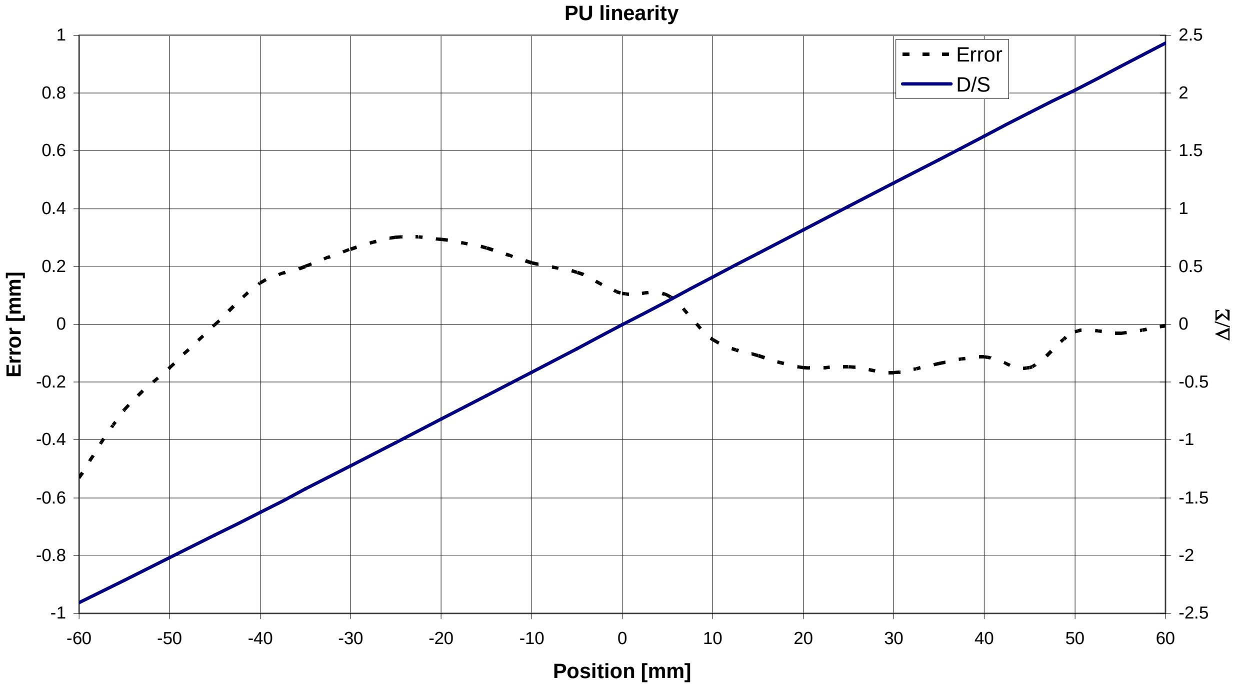

Figure 9: Measured PU linearity, PU diameter =172mm

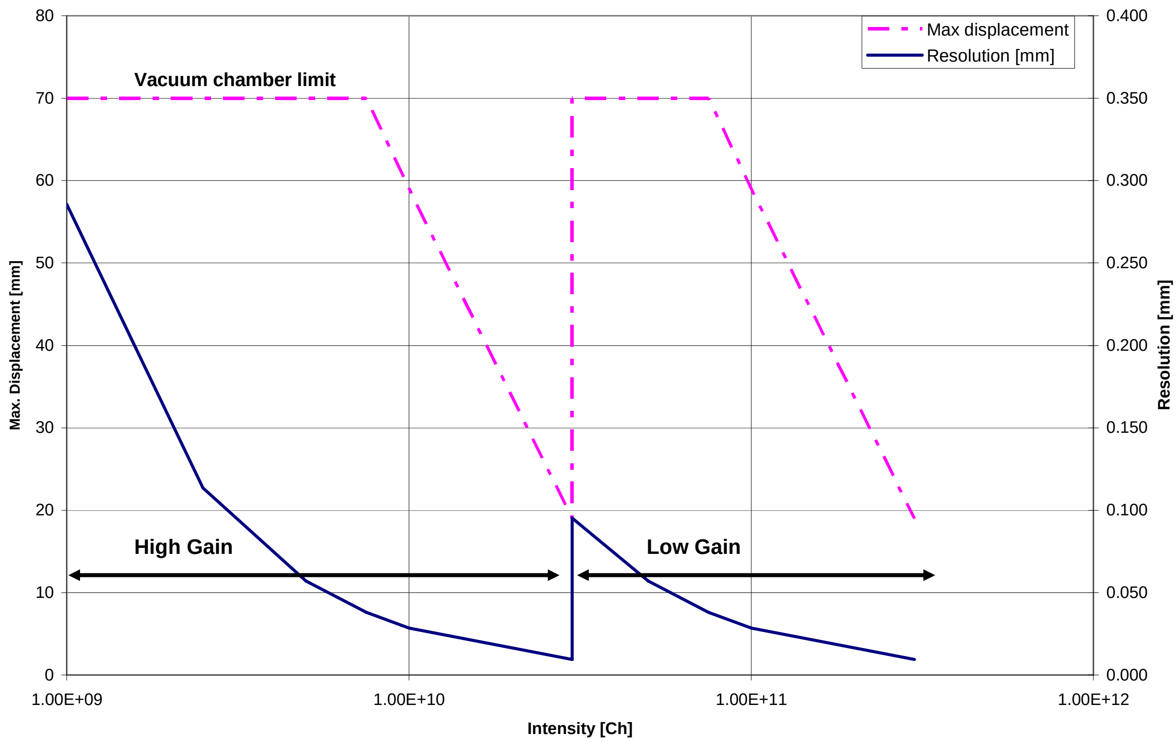

Figure 10: Maximum displacement and resolution as a function of intensity

	High gain	**Low gain**
Gain [dB]	26	6
Bandwidth [MHz]	0.003-100	0.003-100
Droop for 200nS bunch [%]	0.4	0.4
Max intensity per bunch [Ch.]	$3*10^{10}$	$3*10^{11}$
Max displacement @ Max. int. [mm]	19	19
Resolution [mm]	0.3 @ 10^9 Ch.	0.1 @ $3*10^{10}$ Ch.
Max. absolute error in centre [mm]	0.3	0.3
Max. linearity error [%]	1	1
Differential sensitivity [V/mm]	$960*10^{-15}*N*Bf$	$96*10^{-15}*N*Bf$
Intensity sensitivity [V / Ch]	$16.9*10^{-12}$	$1.69*10^{-12}$
Analogue Δ-S/N-ratio @ 1mm. @ min. int.	5 @ 10^9 Ch.	60 @ $3*10^{10}$ Ch.

Table 9: Overall performance

The beam trajectory (registered on 21.04.2006) is shown in Figure 11. The magnets before the last PU were off, so the trajectory in Figure 11 is correct only for the first 6 PUs. The raw ▯ and ▯ signals in the first PU are shown in Figure 6.

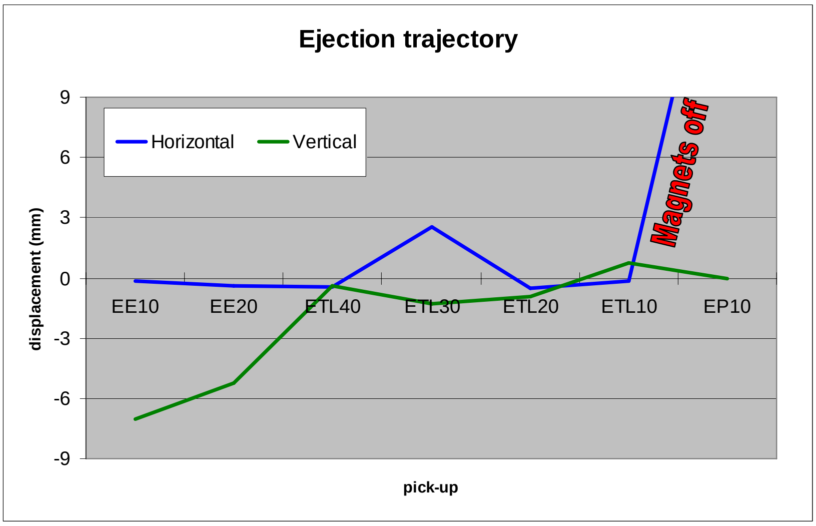

Figure 11: Ejection trajectory

10. Conclusion

For the LEIR trajectory measurement in the transfer line towards the PS, parts of the existing hardware such as PUs (except for 4 units which has been constructed), cables and reception amplifiers are re-used. A new head amplifier, having 2 different gains, was developed and installed. A digital acquisition system, using fast ADCs (200MS/s), has replaced the old analogue integrators, which simplifies the timing requirements and maintenance. The software includes bunch detection and baseline correction before the positions are calculated. Digital integration and normalisation is done in order to calculate the overall position of the 2 bunches. The system was commissioned with beam in the first run of 2006 and is now operational except for a missing application program.